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RF DEFLECTOR BASED MEASUREMENTS OF THE CORRELATIONS BETWEEN VERTICAL AND LONGITUDINAL PLANES AT ELI–NP–GBS ELECTRON LINAC

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Abstract

The correlations between vertical and longitudinal planes at the Radio Frequency Deflector (RFD) entrance can be introduced by misalignments of accelerating sections or quadrupoles upstream of the RFD. These correlations are undesired effects and they can affect the RFD based bunch length measurements in high–brightness electron LINAC. In this paper, an RFD based measurement technique for vertical and longitudinal planes is proposed. The basic idea is to obtain information about the correlations between vertical and longitudinal planes from vertical spot size measurements varying the RFD phase, because they add contributions on this quantity. In particular, considering a small RFD phase range centred in 0 or π rad, the correlations between the particle longitudinal positions and the vertical plane are constant with the deflecting voltage phase, on the contrary, the correlations between the particle energies and the vertical plane vary linearly with the deflecting voltage phase. The simulations are carried out by means of ELEctron Generation ANd Tracking (ELEGANT) code in the case of the Gamma Beam System (GBS) at the Extreme Light Infrastructure–Nuclear Physics (ELI–NP).

INTRODUCTION

RFD or Transverse Deflecting Structure (TDS) [1] are very common in high–brightness LINACs in order to measure the ultra–short electron bunch length since they allow to achieve very good resolutions, lower than other state–of–the–art measurements, such Electro Optical Sampling [2]: at SLAC [3,4], at SPARC_LAB [5,6], at DESY [7], at MIT PSFC [8], and so on. An RFD provides a transverse kick to the electron bunch introducing a relationship between the bunch longitudinal dimension and the bunch vertical dimension at a screen, placed after the RFD. Therefore, the electron bunch length can be obtained through vertical spot size measurements on a screen, placed after the RFD [9,10], after an appropriate calibration measuring the vertical bunch centroid varying the deflecting voltage phase [11].

The correlations between vertical and longitudinal planes at the RFD entrance can be introduced by misalignments of accelerating sections or quadrupoles upstream of the RFD [12]. These correlations are undesired effects and they can affect the bunch length measurements based on the usage of the RFD in high–brightness electron LINAC. The contribution of strong correlations between vertical and longitudinal are not taken into account by means of the standard bunch length measurement technique [4, 5, 11] and, therefore, they can be sources of systematic error. On the other hand, the variations of the squared value of vertical spot size due to these correlations can be used in order to take information about them. In this paper, a measurement technique for the correlations between the vertical and the longitudinal planes by means of an RFD is proposed. First of all, the theory behind the working principle is explained in section **BASIC IDEA**. Secondly, every step of the proposed measurement technique is detailed (section **MODEL OF MEASUREMENT PRODUCTION**) and, then, the simulation results are compared with the theoretical predictions (section **NUMERICAL RESULTS**). The simulations are carried out by means of ELEGANT code [13] in the case of GBS at ELI–NP facility [14].

BASIC IDEA

Modelling the L_{RFD}–long RFD as a $L_{RFD}/2$–long drift space, a vertical kicker, and another $L_{RFD}/2$–long drift space [15, 16], and assuming *(i)* the particle energy can be written in Taylor series stopped at first order around the particle energy average $\langle E \rangle$, and *(ii)* considering an RFD phase range small and centred in 0 rad (or π rad), the contribution of the correlations between longitudinal and vertical planes on the squared value of the vertical spot size at screen after the RFD is:

$$cor_{l_0 v_0}(\varphi) = 2K_{cal}(0) cor_{t_0 v_0} - 2\frac{K_{cal}(0)}{2\pi f_{RF}} cor_{\delta_0 v_0}\varphi, \quad (1)$$

where f_{RF} and φ are the deflecting voltage frequency and phase, respectively, t_0 is the particle longitudinal position in seconds when the bunch centroid is at RFD centre, $\delta_0 = (E_0 - \langle E_0 \rangle)/\langle E_0 \rangle$, E_0 is the particle energy, $cor_{t_0 v_0}$ and $cor_{\delta_0 v_0}$ are *(i)* the correlation term between the particle longitudinal positions and the vertical plane and *(ii)* the correlation term between the particle energies and the vertical plane, respectively:

$$cor_{t_0 v_0} = \sigma_{y_0 t_0} + L\sigma_{y_0' t_0}, \quad (2)$$

$$cor_{\delta_0 v_0} = \sigma_{y_0 \delta_0} + L\sigma_{y_0' \delta_0}, \quad (3)$$

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where y_0 and y_0' are the particle vertical position and divergence, respectively, $\sigma_{y_0t_0}$ and $\sigma_{y_0't_0}$ are *(i)* the covariance between the particle vertical and longitudinal positions and the covariance *(i)* between the particle vertical divergences and longitudinal positions, respectively, $\sigma_{y_0\delta_0}$ and $\sigma_{y_0'\delta_0}$ are *(i)* the covariances between the particle vertical positions and energies and *(ii)* between the particle vertical divergences and energies, respectively, L is the distance between RFD centre and the screen, and $K_{cal}(\varphi)$ is the calibration factor [11, 15]:

$$K_{cal}(\varphi) = 2\pi f_{RF} L C_{RFD0a} cos(\varphi), \quad (4)$$

where $C_{RFD0a} = V_t/\langle E_0 \rangle$ and V_t is the deflecting voltage amplitude. The calibration factor can be calculated through vertical bunch centroid measurements at the screen varying RFD phase in a small range centred in 0 rad (π rad) [11, 17]:

$$K_{cal} = 2\pi f_{RF} p, \quad (5)$$

where p is the slope of the vertical bunch centroid versus deflecting voltage phase. This RFD model neglects the induced energy chirp and energy spread to the bunch. Actually, the TM–like deflecting modes of the cavity has a non–zero derivative of the longitudinal electric field on axis and the deflecting voltage is directly related to the longitudinal electric field gradient through the Panofsky–Wenzel theorem inducing an energy chirp and spread to the bunch [11, 18].

The contribution of strong correlations between vertical and longitudinal are undesired effects for the standard bunch length measurement technique and, therefore, they can be sources of systematic error. On the other hand, the variations of the squared value of vertical spot size due to these correlations can be used in order to take information about them. First of all, these contributions have to be isolated from the contributions of the vertical spot size at the screen with RFD on: *(i)* the vertical spot size at the screen with RFD off, *(ii)* the bunch length term, *(iii)* the energy chirp term, and *(iv)* the energy spread term [19]. The idea is based on this property: for the deflecting voltage phases φ and $\varphi + \pi$, all the terms do not change their values, but the correlation contributions change sign and, on the contrary, the other terms do not change their signs. For these reasons the correlation contributions can be obtained by means of the following equation:

$$\begin{aligned} cor_{l_0v_0}(\varphi) &= \frac{\sigma_{y_s}^2(\varphi) - \sigma_{y_s}^2(\varphi+\pi)}{2} = \\ &= 2K_{cal}(0) cor_{t_0v_0} - 2\frac{K_{cal}(0)}{2\pi f_{RF}} cor_{\delta_0v_0}\varphi, \end{aligned} \quad (6)$$

where σ_{y_s} is the vertical spot size at screen with RFD on. Secondly, the information about the correlations can be found by means of a linear fit: the slope depends on the correlations between the particle energies and the vertical plane, and the intercept is related to the correlations between the particle longitudinal positions and the vertical plane (see 6):

$$p_{cor} = -\frac{K_{cal}(0)}{\pi f_{RF}} cor_{\delta_0v_0}, \qquad cor_{\delta_0v_0,m} = -\frac{\pi f_{RF}}{K_{cal}(0)} p_{cor}; \quad (7)$$

$$q_{cor} = 2K_{cal}(0) cor_{t_0v_0}, \qquad cor_{t_0v_0,m} = \frac{q_{cor}}{2K_{cal}(0)}. \quad (8)$$

MODEL OF MEASUREMENT PRODUCTION

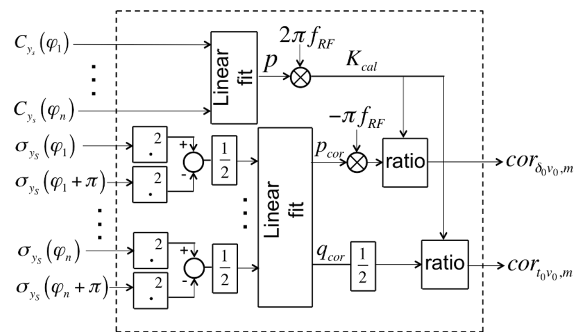

Figure 1: Model of measurement production.

From the considerations of section **BASIC IDEA**, the model of measurement production in Fig. 1 for the correlations between vertical and longitudinal planes can be thought. The model relies on two main stages: the measurements and the data processing. The former stage consists of the following operations:

1. measurements of the vertical bunch centroid at screen for different values of the deflecting voltage phase φ_i in a small range centred in 0 rad (or π rad): $C_{y_s}(\varphi_i)$;

2. measurements of the vertical spot size at screen varying the deflecting voltage phase φ_i in a small range centred in 0 rad: $\sigma_{y_s}(\varphi_i)$;

3. measurements of the vertical spot size at screen for the deflecting voltage phase $\varphi_i + \pi$: $\sigma_{y_s}(\varphi_i + \pi)$.

The data processing stage consists of the following steps:

1. estimation of the slope p of the plot vertical bunch centroid at screen versus φ by means of a linear fit, and then calculate the calibration factor K_{cal} by multiplying the deflecting voltage angular frequency by the slope p (5);

2. estimation of the half of differences between the squared values of the vertical spot sizes $\sigma_{y_s}(\varphi_i)$ and $\sigma_{y_s}(\varphi_i + \pi)$ (from 6): $cor_{l_0v_0}(\varphi_i)$;

3. evaluation of the correlation term *(i)* between the particle energies and the vertical plane $cor_{\delta_0v_0,m}$ and *(ii)* between the particle longitudinal positions and the vertical plane $cor_{t_0v_0,m}$ from (7) and (8), respectively.

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NUMERICAL RESULTS

Case Study

ELI–NP is one of the pillars of the ELI European project dedicated to high–level research on ultra–high intensity laser, laser–matter interaction, and secondary sources [20]. The GBS at ELI–NP will be an advanced source of up to 20 MeV gamma rays based on Compton back–scattering (i.e. collision of an intense high power laser beam and a high brightness electron beam with maximum kinetic energy of about 720 MeV [14]) in Romania. The GBS electron LINAC can run at a maximum repetition rate of 100 Hz [21], and, therefore, the specifications on the requested spectral density (1×10^4 photon/(eV s)) cannot be achieved with single bunch collisions at room temperature [14]. The final optimization foresees multiple bunch collisions, with trains of 32 electron bunches, 1 ps in length, with a repetition period of 16 ns, distributed along a 500 ns RF pulse. The laser pulse should collide with all the electron bunches in the RF pulse before being dumped, therefore the RF LINAC has to provide bunches in each train equally spaced for recirculating the laser pulse in a suitable device [14]. Moreover, the electron bunch length must be tuned according to the laser bunch length. Consequently, the measurement of the properties of the single bunch and the whole train of bunches is a crucial task for beam diagnostic [22].

Simulation Condition

A bunch composed of 50,000 particles with a charge of 250 pC was tracked by means of ELEGANT code from the RFD to the screen of GBS electron LINAC, placed between the first and the second C–band accelerating section of GBS electron LINAC [14]. The distance between RFD centre and the screen L is 1.1380 m. The deflecting voltage amplitude V_t and frequency are 1 MeV and 2.856 GHz, respectively. The GBS electron LINAC bunch parameters of vertical and longitudinal planes at RFD entrance are (in RMS): σ_y =356 μm, $\sigma_{y'}$ =60.1 μrad, $\sigma_{yy'}$ =−19.6 mm μrad, $\langle E \rangle$ =118 MeV, σ_t =0.912 ps, and $\sigma_{t\delta}$ =5.33 fs.

It is useful to introduce the correlation coefficient in order to quantify the correlations between the vertical and the longitudinal planes:

$$r_{hk} = \frac{\sigma_{hk}}{\sigma_h \sigma_k}. \tag{9}$$

The correlation coefficient quantifies how much two bunch parameters are correlated: when $r_{hk} = 0$ the bunch parameters h and k are not correlated, when $r_{hk} = |1|$ they are strongly correlated ($r_{hk} = -1$ negative correlated and $r_{hk} = 1$ positive correlated) [23]. The correlation factors at RFD entrance used in the simulations are: *(i)* between particle longitudinal positions and the vertical plane $r_{yt} = 0.107$ and $r_{y't} = 0.290$, and *(ii)* between particle energies and the vertical plane $r_{y\delta} = 0.103$ and $r_{y'\delta} = 0.277$. They can be introduced by the misalignments of the first accelerating section and the first quadrupole upstream of the RFD of −2 mm.

Correlation Measurements

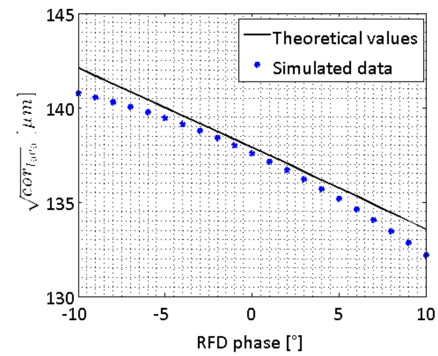

Figure 2: $\sqrt{cor_{t0v0}}$ versus deflecting voltage phase. Simulated data in blue stars (i.e. the square root of the half of the difference of squared vertical spot size measurements at screen with deflecting voltage phase φ and $\varphi + \pi$), and theoretical values (1) in black line.

The assumption of a constant calibration factor in a range of 20° centred in 0° (or 180°) is well–satisfied for the case study [19]. In Fig. 2, $\sqrt{cor_{t0v0}}$ versus deflecting voltage phase is plotted (simulated data in blue stars, i.e. the square root of the half of the difference of squared vertical spot size measurements at screen with deflecting voltage phase φ and $\varphi + \pi$, and theoretical values (1) in black line). In this scenario, the contributions of the correlations between vertical and longitudinal planes on the vertical spot size are in the order of hundreds of micron. The correlation measurements are: $cor_{\delta_0 v_0,m}$ = (0.348 ± 0.011) μm and $cor_{t_0 v_0,m}$ = (54.41 ± 0.06) μm ps (the uncertainties take into account only the uncertainties due to the linear fits), with a relative error (i.e. the difference between true and measured values over true value) of the order of 3%.

CONCLUSIONS

In this paper, an RFD based measurement technique for vertical and longitudinal planes is proposed. The basic idea is to obtain information about the correlations between vertical and longitudinal planes from vertical spot size measurements varying the RFD phase, because they add contributions on this quantity. The simulations are carried out by means of ELEGANT code in the case of GBS at ELI–NP facility. In this case study, strong correlations at RFD entrance between vertical and longitudinal planes are introduced in order to add a significant contribution to the vertical spot size at screen: between particle longitudinal positions and vertical plane $r_{yt} = 0.107$ and $r_{y't} = 0.290$, and between particle energies and vertical plane $r_{y\delta} = 0.103$ and $r_{y'\delta} = 0.277$. They can be introduced by the misalignments of the first accelerating section and the first quadrupole upstream of the RFD of −2 mm. The correlation measurements are: $cor_{\delta_0 v_0,m} = (0.348 \pm 0.011)$ μm and

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$cor_{t_0 v_0, m} = (54.41 \pm 0.06)$ μm ps (the uncertainties take into account only the uncertainties due to the linear fits), with a relative error (i.e. the difference between true and measured values over true value) of the order of 3%.

REFERENCES

[1] A. Cianchi *et al.*, "Observations and Diagnostics in High Brightness Beams", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 829, pp. 343–347, 2016.

[2] R. Pompili *et al.*, "First Single–Shot and Non–Intercepting Longitudinal Bunch Diagnostics for Comb–Like Beam by Means of Electro–Optic Sampling", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 740, pp. 216–221, 2014.

[3] R. Akre, L. Bentson, P. Emma, and P. Krejcik, "A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics", in *Proc. of Particle Accelerator Conference (PAC), 2001*, pp. 2353–2355.

[4] R. Akre, L. Bentson, P. Emma, and Krejcik, "Bunch Length Measurements Using a Transverse RF Deflecting Structure in the SLAC LINAC" , in *Proc. of European Particle Accelerator Conference (EPAC), Paris, France, 2002*, pp. 682–685.

[5] D. Alesini *et al.*, "RF Deflector Design and Measurements for the Longitudinal and Transverse Phase Space Characterization at SPARC" *, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 568, no. 2, pp. 488–502, 2006.

[6] D. Filippetto *et al.*, "Phase Space Analysis of Velocity Bunched Beams", *Physical Review Special Topics-Accelerators and Beams*, vol. 14, no. 9, p. 092804, 2011.

[7] M. Hüning *et al.*, "Observation of Femtosecond Bunch Length Using a Transverse Deflecting Structure", in *Proc. of the 27th International Free Electron Laser Conference (FEL), Stanford, CA, USA, 2005*.

[8] J. Haimson, "Longitudinal Phase Space Measurements of Short Electron Bunches Using a 17 GHz Circularly Polarized Beam Deflector", in *AIP Conference Proceedings*, vol. 737. AIP, 2004, pp. 95–108.

[9] R. H. Miller, R. F. Koontz, and D. D. Tsang, "The SLAC Injector", *IEEE Transactions on Nuclear Science*, vol. 12, no. 3, pp. 804–808, 1965.

[10] X. J. Wang, "Producing and Measuring Small Electron Bunches", in *Proc. of Particle Accelerator Conference (PAC), New York, USA.*, 1999, pp. 229–233.

[11] D. Alesini *et al.*, "Sliced Beam Parameter Measurements", in *Proc. of DIPAC, Basel, Switzerland*, 2009.

[12] P. Emma, J. Frisch, and P. Krejcik, "A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics", *LCLS Technical Note*, vol. 12, 2000.

[13] M. Borland, "Elegant: A flexible sdds-compliant code for accelerator simulation", Argonne National Lab., IL (US), Tech. Rep., 2000.

[14] O. Adriani *et al.*, "Technical design report eurogammas proposal for the eli-np gamma beam system", *arXiv preprint arXiv:1407.3669*, 2014.

[15] L. Sabato, P. Arpaia, A. Giribono, A. Liccardo, A. Mostacci, L. Palumbo, C. Vaccarezza, and A. Variola, "Effects of Energy Chirp on Bunch Length Measurement in Linear Accelerator Beams", *Measurement Science and Technology*, vol. 28, no. 8, p. 084002, 2017. [Online]. Available: https://doi.org/10.1088/1361-6501/aa6c8a

[16] A. Cianchi, "Observations and Diagnostics in High Bbrightness Beams", in *Proc. of CERN Accelerator School (CAS), Intensity Limitations in Particle Beams, Geneva, Switzerland*, November 2015.

[17] L. Sabato, D. Alesini, P. Arpaia, A. Giribono, A. Liccardo, A. Mostacci, P. L, C. Vaccarezza, and V. A, "Metrological Characterization of the Bunch Length System Measurement of the ELI–NP Electron LINAC", in *Proc. of 14th IMEKO TC10, Milan, Italy, June 2016*, pp. 203–208.

[18] C. Behrens *et al.*, "Measurement and Control of the Longitudinal Phase Space at High–Gain Free–Electron Lasers", in *Proc. of 33rd International Free Electron Laser Conference, Shanghai, China, 2011*.

[19] L. Sabato, P. Arpaia, A. Liccardo, A. Mostacci, L. Palumbo, and A. Variola, "Energy Chirp Measurements by Means of an RF Deflector: a Case Study the Gamma Beam Source LINAC at ELI-NP", in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May, 2017*. Geneva, Switzerland: JACoW, 2017, paper MOPAB059, pp. 242–245.

[20] C. A. Ur *et al.*, "The ELI–NP Facility for Nuclear Physics", *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 355, pp. 198–202, 2015.

[21] A. Bacci *et al.*, "Electron LINAC Design to Drive Bright Compton Back–Sscattering Gamma–Ray Sources", *Journal of Applied Physics*, vol. 113, no. 19, p. 194508, 2013.

[22] A. Cianchi *et al.*, "Six–Dimensional Measurements of Trains of High Brightness Electron Bunches", *Physical Review Special Topics–Accelerators and Beams*, vol. 18, no. 8, p. 082804, 2015.

[23] F. L. Coolidge, *Statistics: A Gentle Introduction*. Sage Publications, 2012.